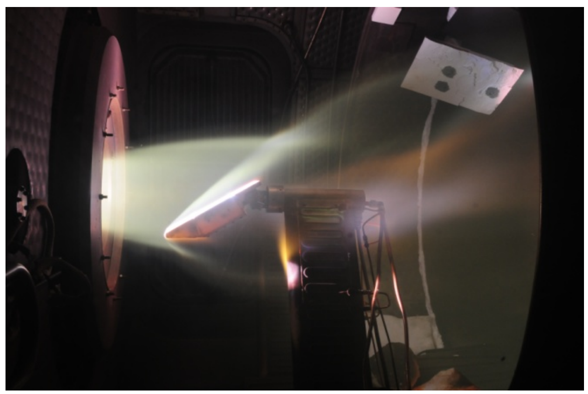
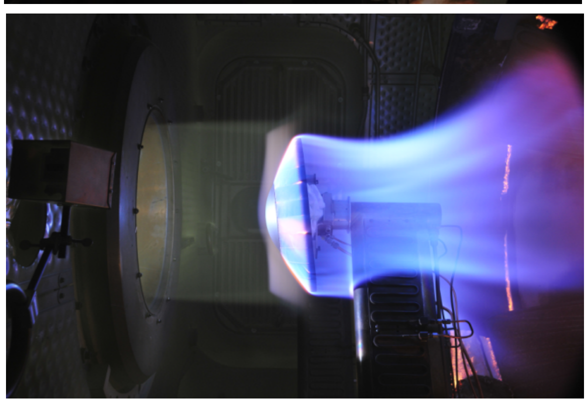
The Development of a CO_2 Test Capability in the NASA JSC Arc Jet for Mars Entry Simulation

IPPW-8 – Portsmouth, Virginia – June 6-10, 2011





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- Entry Simulation and Facility Overview
- Rationale for CO_2
- Safety Concerns and Mitigation
- Exhaust Gas Data
- Flowfield Analysis
- Conclusions
- Forward Work

Arc Jets are

The Best

Ground Simulation of Reentry Environments

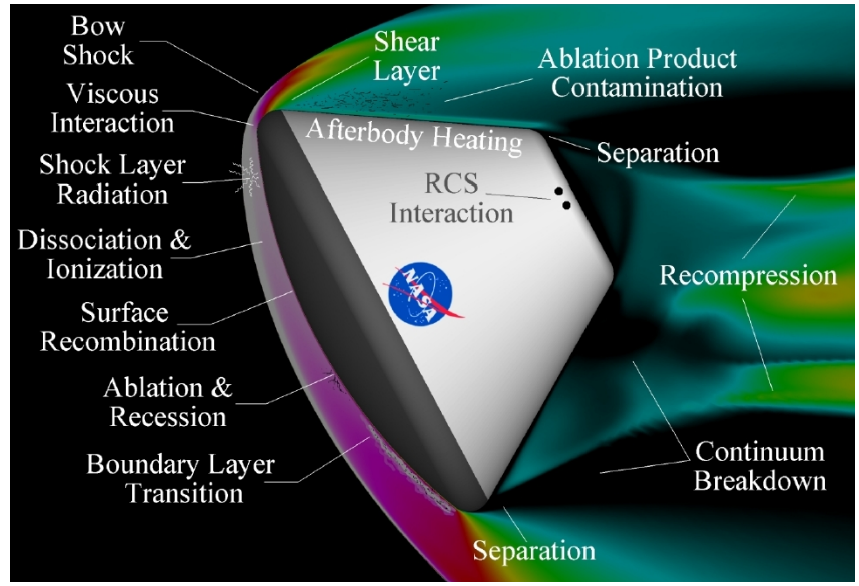
BUT

Arc-jets

Do Not Replicate

Flight

Hypersonic Flow → Atmosphere



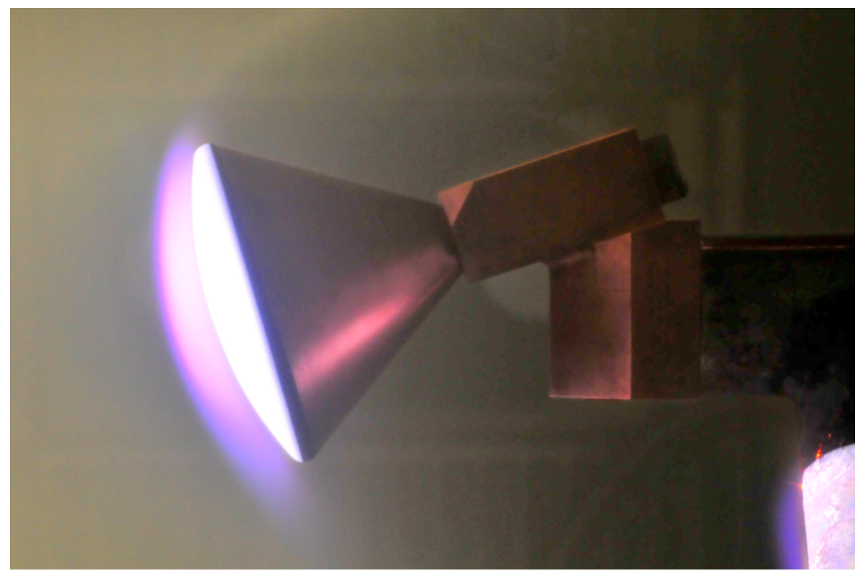
The surface of the model experiences a flight relevant environment in terms of:

- Heating rate
- Pressure
- Chemistry

However, there are differences in:

- Enthalpy
- Boundary layer thickness
- Shear
- Dissociation levels

Supersonic Flow → High Enthalpy Dissociated Gas



Aerodynamically Stabilized Arc Heater

Multi-pack dual diameter constricted arc column
- 1.5-in ID at the cathode, 2.36-in ID downstream

Individually water-cooled, electrically insulated constrictor segments
- 20 segments per modular pack
- 10 pack heater covers the Orbiter environmental envelope
- Arc column can be tailored to specific test conditions by adding or removing packs

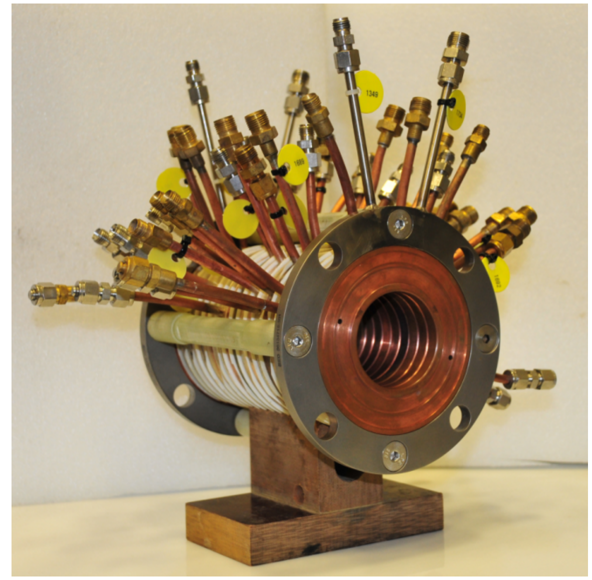
Tungsten button cathode and conical copper anode

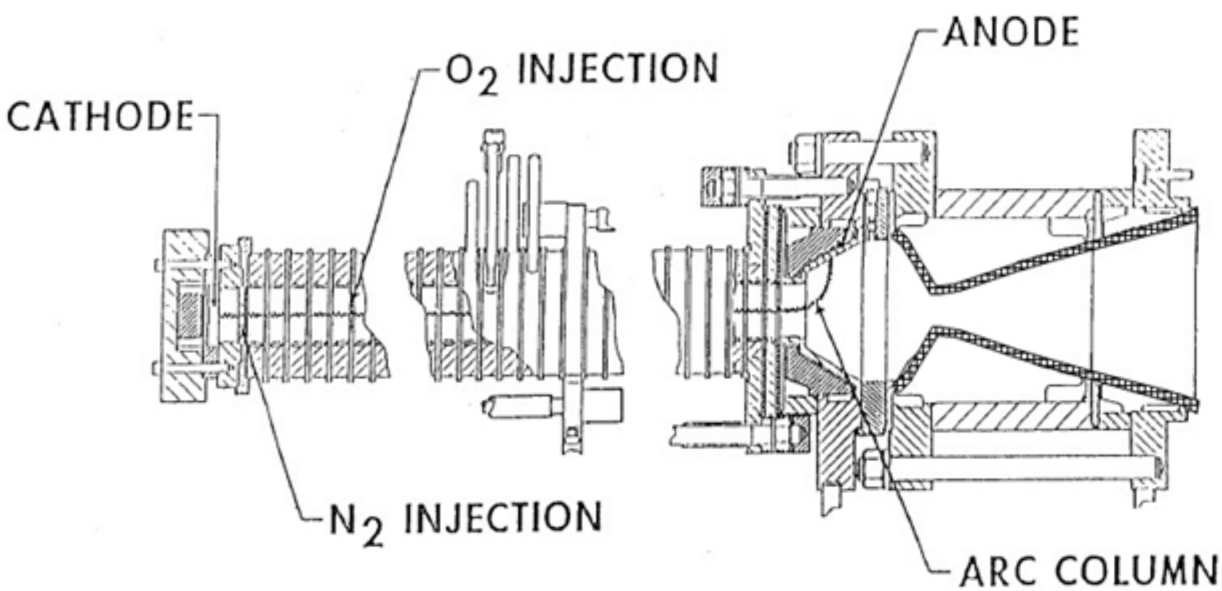
Test gas is injected tangentially to the inner column
- Forms a vortex that stabilizes the electric arc

Bulk enthalpy of the test gas is calculated
- Corrected for energy losses to coolant water

Argon is utilized as a “start” gas to initiate the arc

After “arc on” the control system flows N_2 and O_2 and shuts off the argon





General Facility Description

Solid-state power supply with four current controlled DC rectifiers
- 10MW continuous rating, 13MW for 30 minutes

4 stage steam ejector vacuum system
- 200 microns Hg, ~192,000-ft altitude
- Steam is provided by an 80,000 lbm/hr boiler
- Up to 1.5 lbm/sec test gas capacity

Two test positions (TP-1 and TP-2)

Test gases (N_2 and O_2) and start gas (Argon)
- Individually controlled

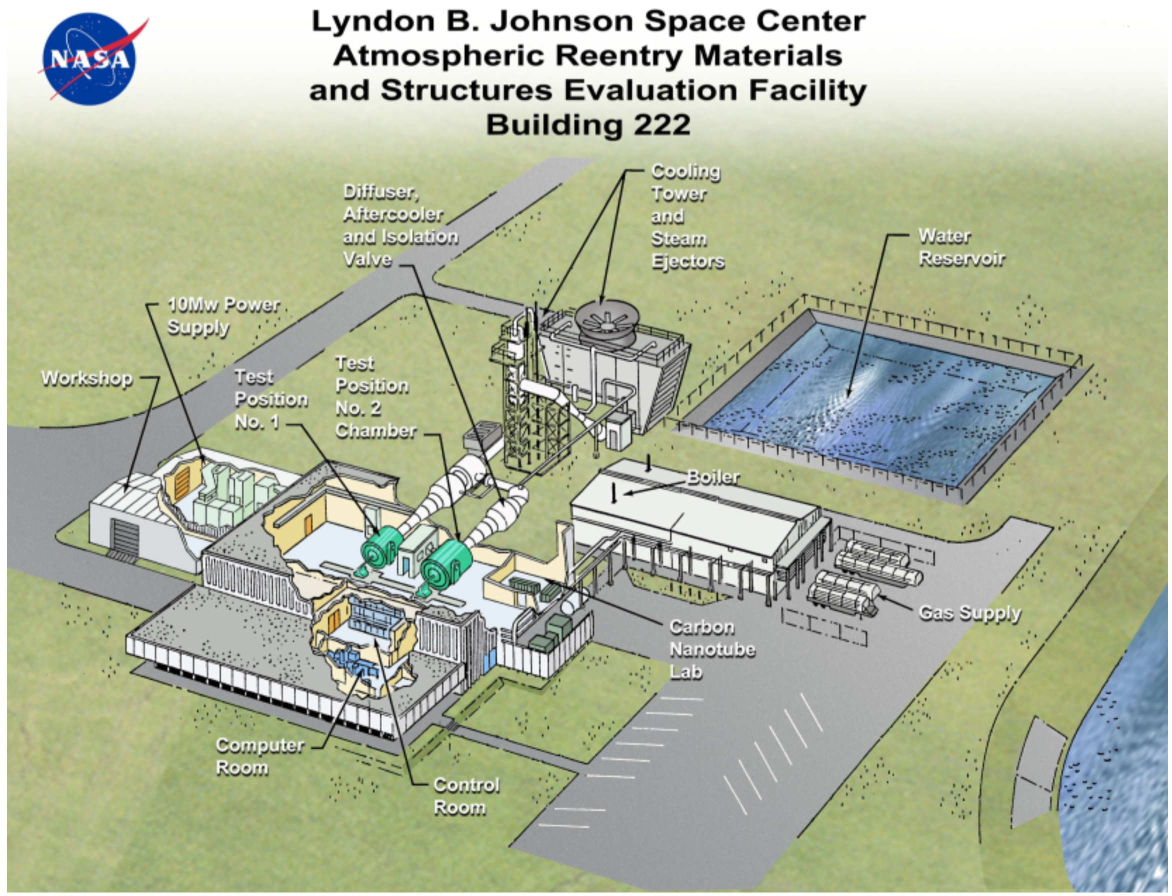
High pressure coolant system
- 500-psi supplied by 700-hp pump
- De-ionized water
- Used for the heater, sting arms, and model holders

Low pressure cooling system
- Approx 30-psi
- Used for the test chamber, diffuser, heat exchangers, etc.

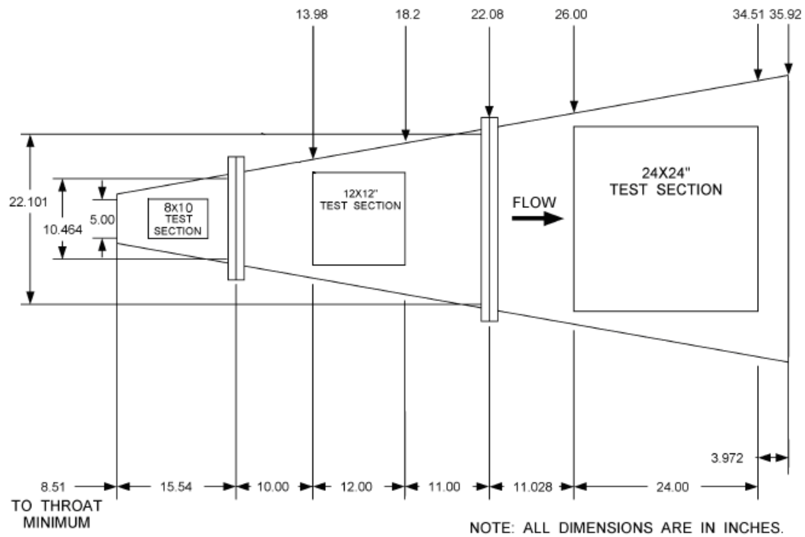
10 Hz data acquisition system
- Up to 200 channels

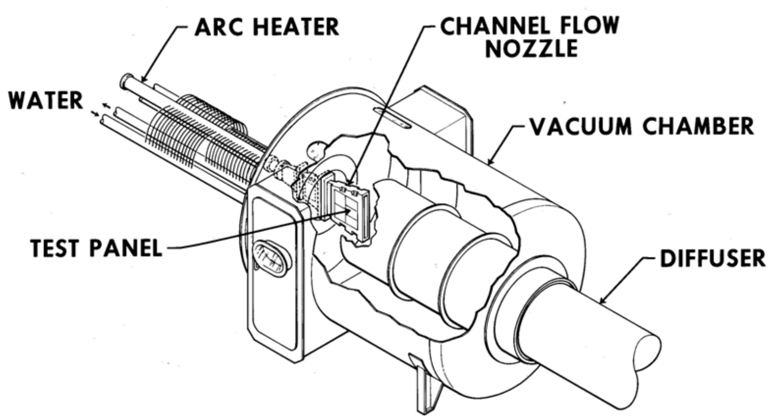
Control system by ABB
- Highly reliable, used in industries worldwide

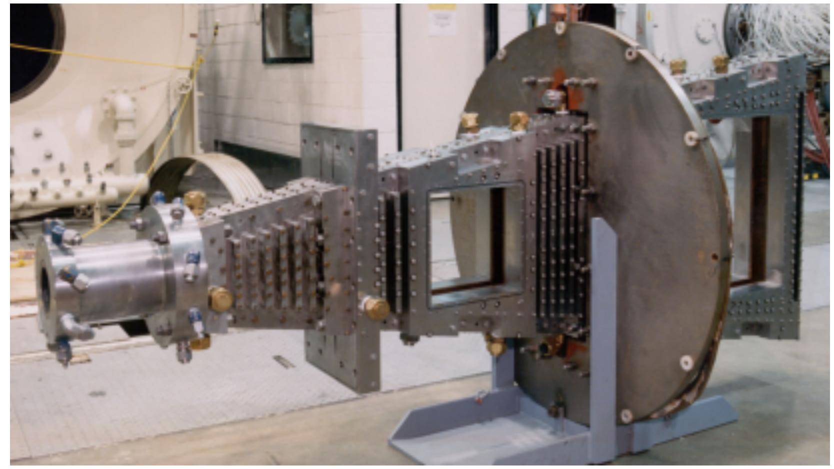
Capable of extended run times
- Multiple hours if necessary

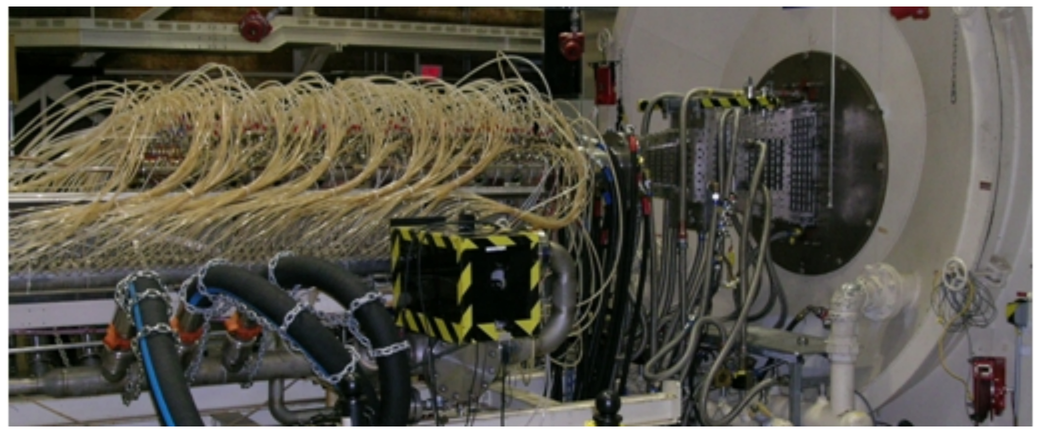


Channel Nozzle (TP-1)





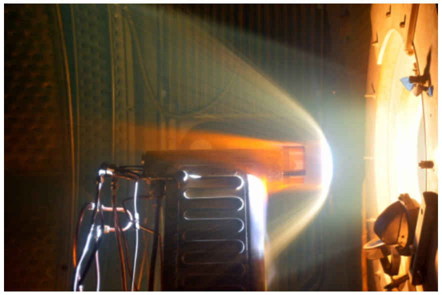




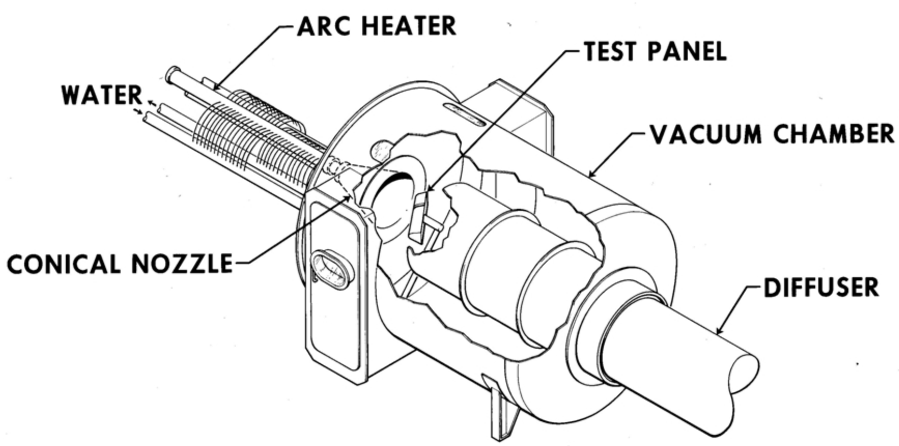
2-in wide, 10° half angle duct
Parallel flow field
10-ft diameter test chamber
- Panels, TPS tile arrays
- Laminar or turbulent flow

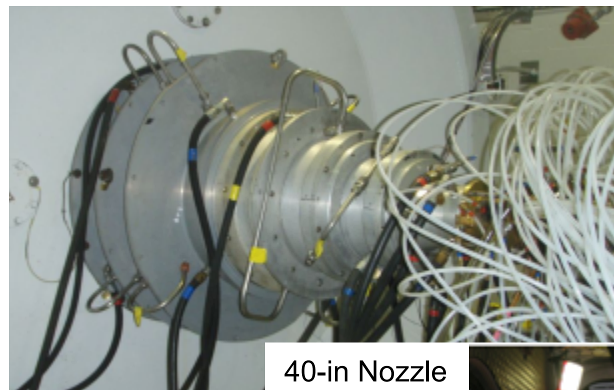
Test Section	Surface Temp Range (°F)	Surface Press Range (psf)
8x10	1500 - 3000	15 - 130
12x12	1000 - 2500	10 - 110
24x24	700 - 2200	5 - 60

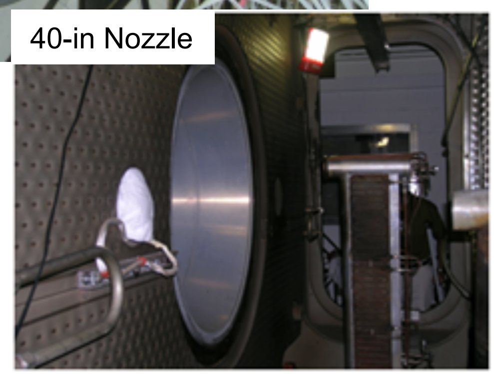
Conical Nozzle (TP-2)



X-33 Wing Leading Edge







40-in Nozzle

Variety of nozzle exit diameters

- 3.5, 5, 7.5, 10, 15, 20, 25, 30, 35, 40-in
- 15° half angle
- Nozzle size and Z-distance determines maximum models size

12-ft diameter test chamber layout allows video and optical temperature measurements of the test article surface

- Mars atmosphere can contain as much as 97% CO_2 by volume
  - For low enthalpy conditions...

$$CO_2 \rightarrow CO + O - 2.9 eV/molecule$$

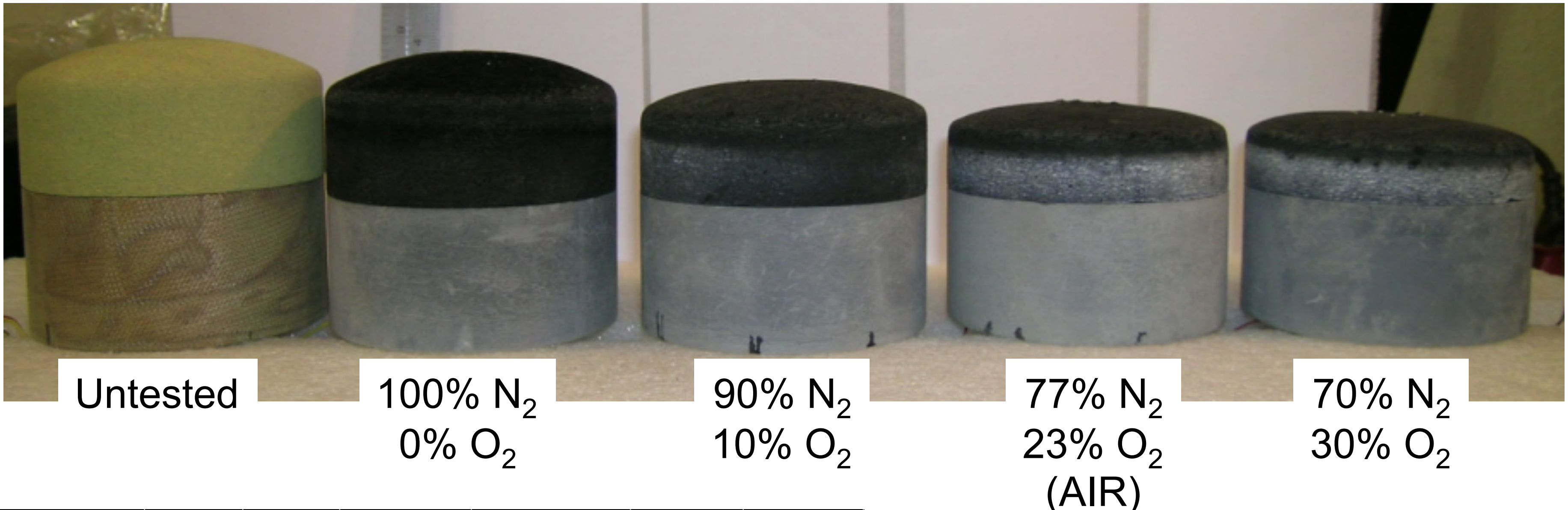
    - Results in more than 35% atomic oxygen by mass
  - With increasing enthalpy...

$$CO \rightarrow C + O - 11.2 eV/molecule$$

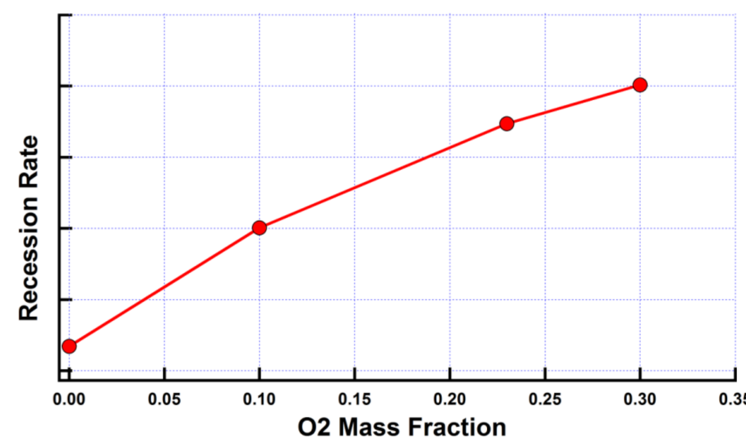
    - Results in ~70% atomic oxygen by mass

- Understanding the response of TPS in this environment is required for accurate modeling
  - Optimized TPS design maximizes payload

PICA Sensitivity to O_2 Variation (January 2008)



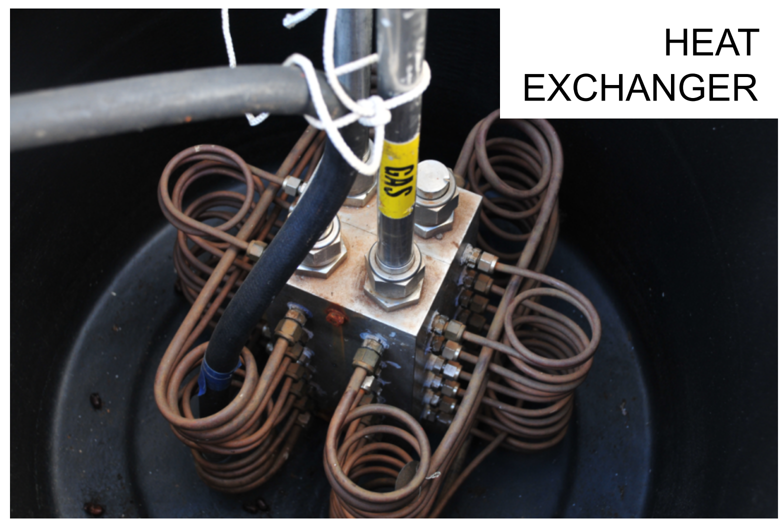
Summary of Dual Cal and Slug Calorimeter Test Conditions (8 inch Z Dist)						
Test Condition	Flow Rate	Current	Bulk Enthalpy	Dual Cal Heat Flux	Pressure	Slug Heat Flux
	lbm/sec	amps	BTU/lbm	BTU/ft^2-sec	(lbf/ft^2)	W/cm^2
100% N_2	0.60	480	2340	268	375	421
10% O_2	0.57	510	2549	256	386	427
23% O_2 (AIR)	0.57	580	2692	258	384	424
30% O_2	0.55	650	2960	257	385	404



- 4-in diameter blunt hemisphere PICA pucks
- Comparable stagnation heat flux and pressure
- Equivalent test durations
- O_2 percentage by mass

CO_2 System Setup

- 18 manifolded CO_2 K bottles used as the supply
- Heat exchanger with hot water from the low pressure boiler is used to prevent the formation of dry ice
- A throttle valve is used to manually control the flow rate based on the heater manifold pressure
  - The O_2 supply manifold on the heater is used as the CO_2 injection site
  - A correlation of manifold pressure to O_2 flow rate is determined beforehand
  - Using a molar mass ratio, the CO_2 flow rate is calculated based on the manifold pressure
  - Corrections to the bulk enthalpy must be applied based on the calculated flow rate



Safety Concerns and Mitigation

- Carbon Monoxide
  - Standard temperature pressure environment
    - 12% LEL and 75% UEL by volume
  - Mitigation via N_2 addition within vacuum system
    - 5:1 N_2:CO_2 is stoichiometrically impossible to explode even with 100% molar conversion of CO_2 to CO

$$CO_2 + 5N_2 + |E| \rightarrow CO + \tfrac{1}{2}O + 5N_2 \quad (\sim>15\%\ CO\ \text{molar},\ 10\%\ CO\ \text{vol.})$$

    - Residual gas analyzer (RGA) is used to sample the cooled exhaust gases to determine actual conversion rate
- Cyanide
  - A cyanide ion can be produced by

$$CO_2 + N_2 + |E| \rightarrow CN^- + O_2 + \tfrac{1}{2}N_2$$

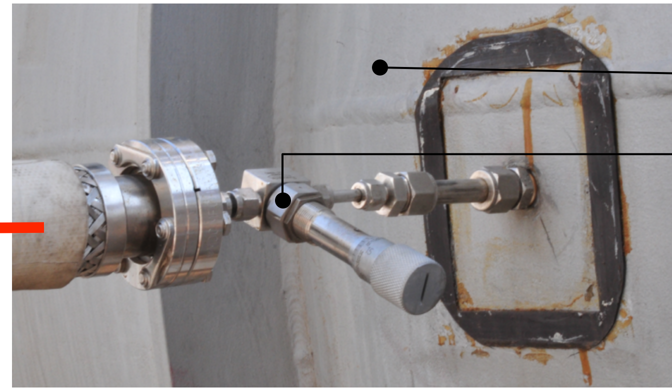
  - Further interaction of the cyanide ion with water can produce hydrogen cyanide by

$$CN^- + H_2O \rightarrow HCN + OH^-$$

  - JSC Industrial Hygiene (IH) office analyzed chamber surface and water samples
    - To date, all samples reported as "non-detect" (< 1-μg/ft^2)
- Carbon Deposition
  - Complete dissociation of the CO_2 could result in carbon soot deposits on the internal heater parts. Catastrophic failure could then occur due to electrical shorting.
  - Mitigation via performing tests beginning at low CO_2 concentrations and short durations and inspecting the heater after each test run
  - To date there has been no carbon deposition

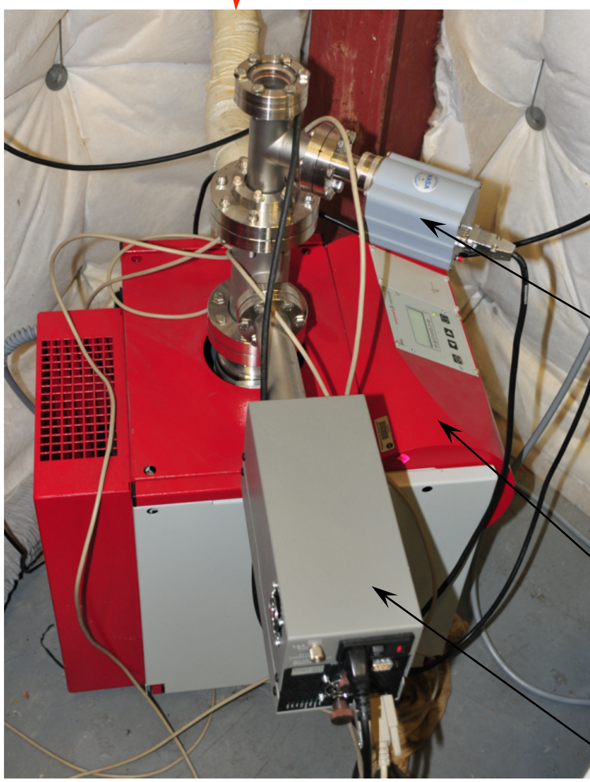
Residual Gas Analyzer Setup

Exhaust Gas Sample



Outer Diffuser Skin

Metering Valve



MKS Instruments 999 Quattro™ Multi-Sensor Vacuum Transducer
5.0×10^{-10} Torr to Atmosphere
With Atmospheric Switching

Pfieffer Vacuum HiPace-80 Pumping Station

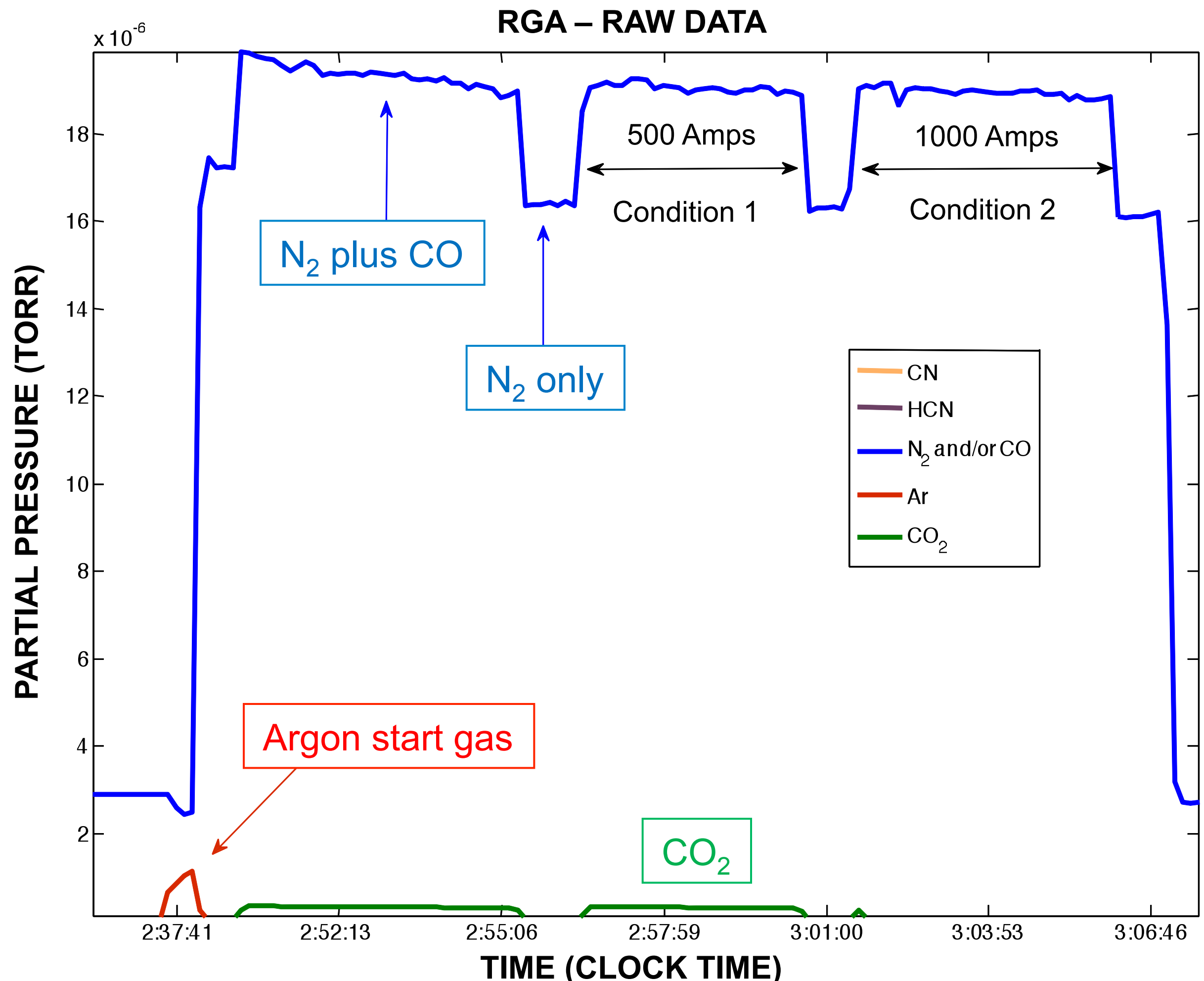
Stanford Research Systems RGA300

Vacuum is set to 10^{-6} torr prior to test and rises to ~10^{-5} torr during sampling exhaust gases

- Test run 2-3710-1 (January 2011)
  - 46% CO_2 by mass
  - 0.22-lb/sec total gas
  - ~55% molar conversion

	Cond 1	Cond 2
Current (amps)	500	1000
Power (MW)	1.32	2.33
Bulk Enthalpy (BTU/lb)	4170	6670
Stag Heat Rate* (BTU/ft^2-sec)	148	352
Stag Pressure* (psf)	155	200

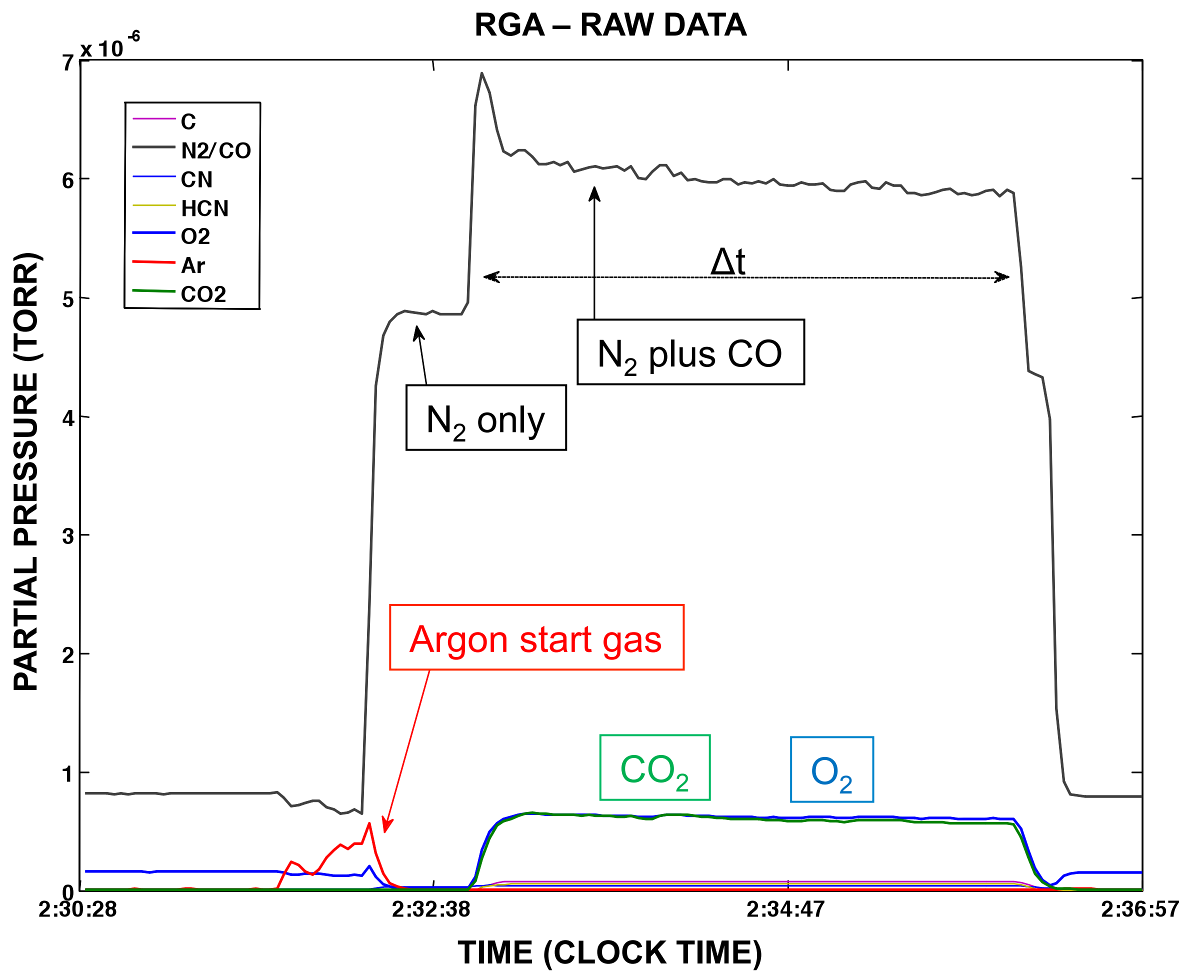
*4 inch diameter flat face



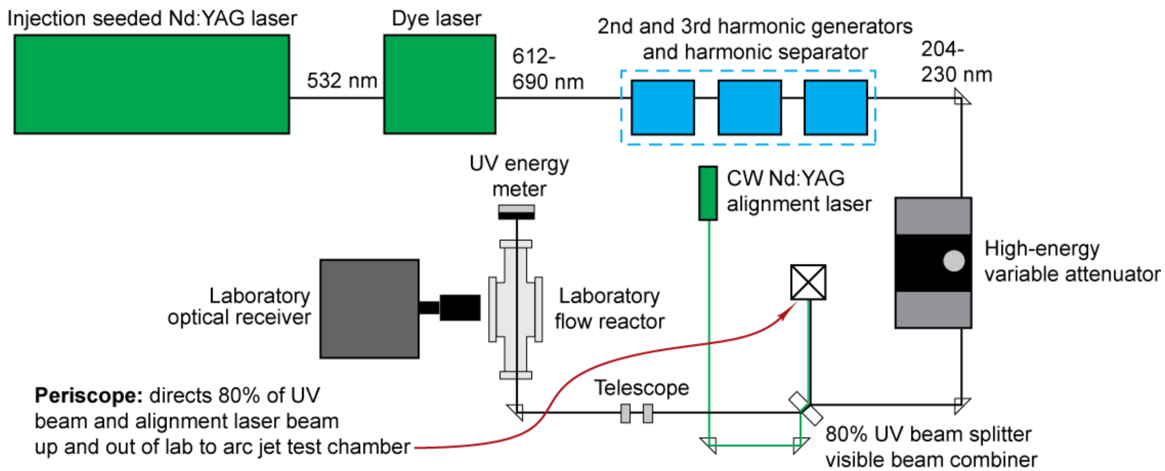
- Test run 2-3730-1 (March 2011)
  - 90% CO_2 by mass
  - 0.40-lb/sec total gas
  - ~ 60% molar conversion

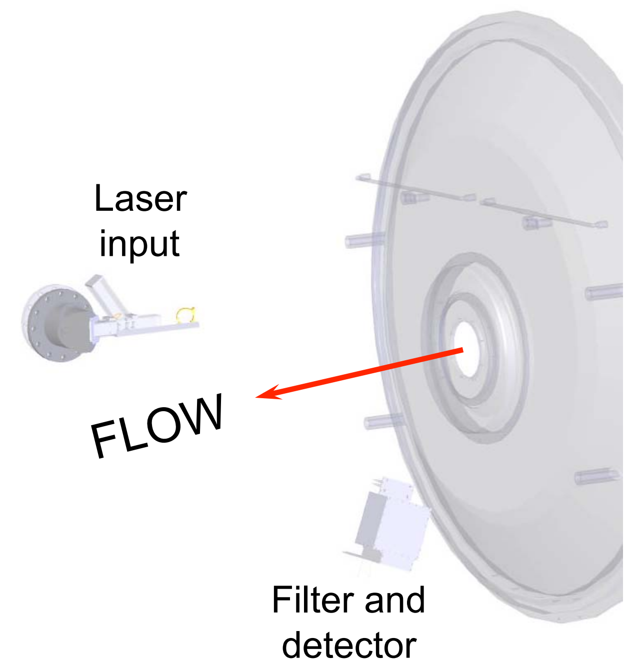
Current (amps)	750
Power (MW)	2.52
Bulk Enthalpy (BTU/lb)	4910
Stag Heat Rate* (BTU/ft^2-sec)	185
Stag Pressure* (psf)	265

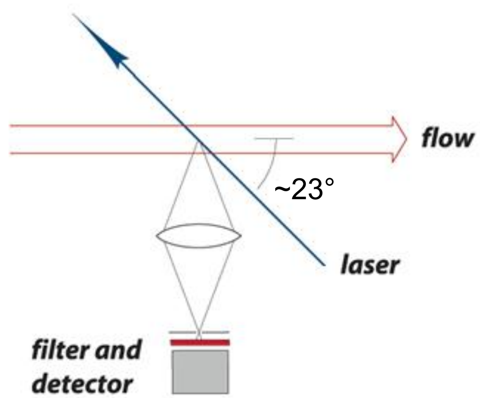
*4 inch diameter flat face

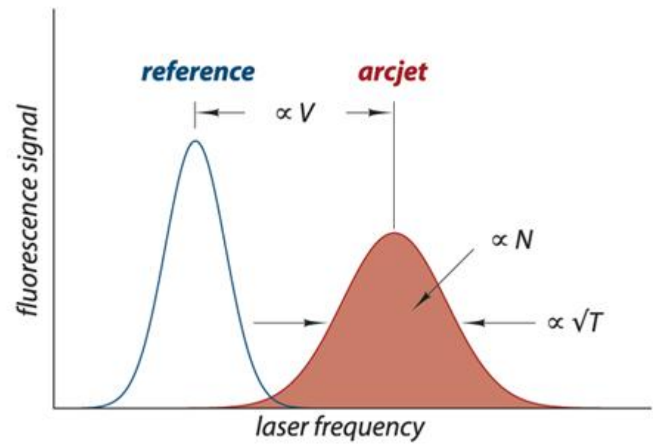


Flow Field Characterization using Laser Induced Fluorescence (LIF)



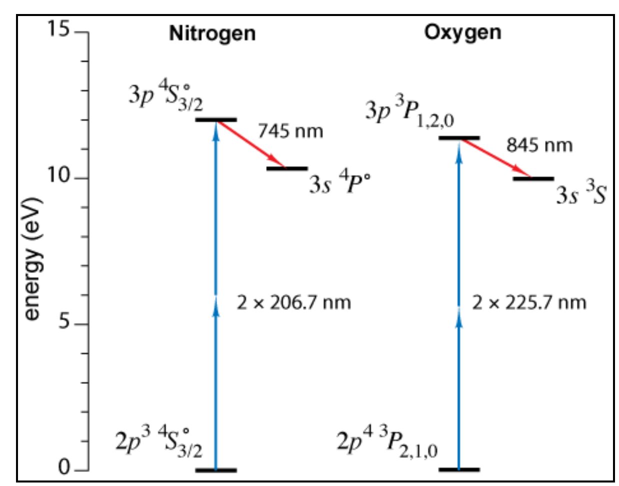






Laser frequency is tuned to interrogate O and N species independently

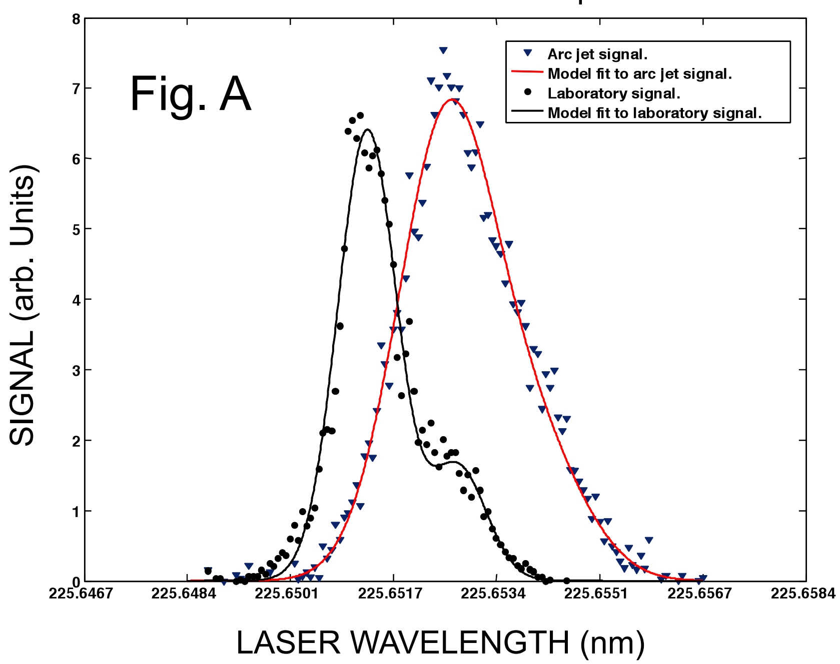
Fluorescence signal reveals three important flow properties
- Velocity from Doppler shift
- Temperature from lineshape width
- Species density from total signal intensity



Atomic Oxygen LIF Data, Test Run 2-3710-1 (January 2011)

- 46% CO_2 : 54% N_2 by mass
- 0.220-lb/sec total gas

O-atom LIF – 500 Amps



O-atom LIF – 1000 Amps

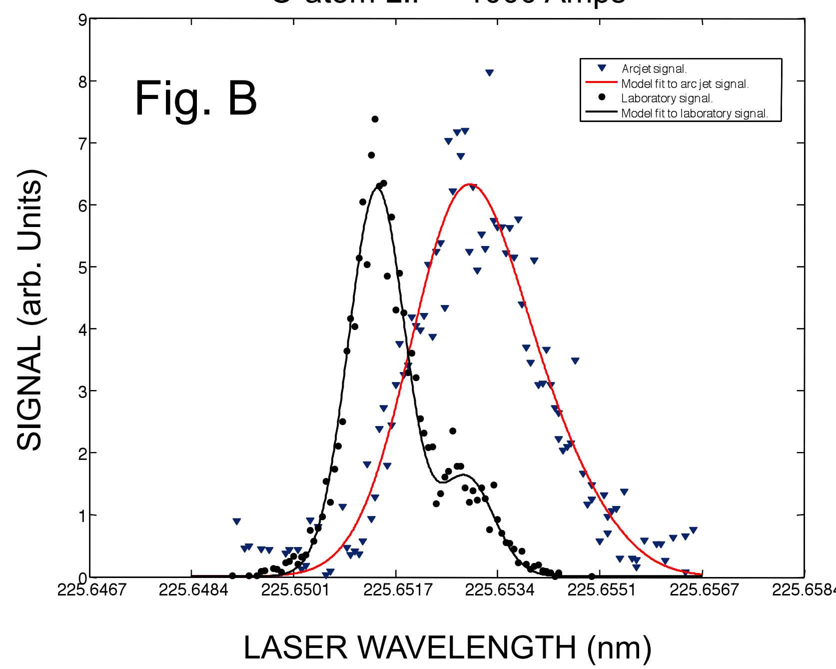
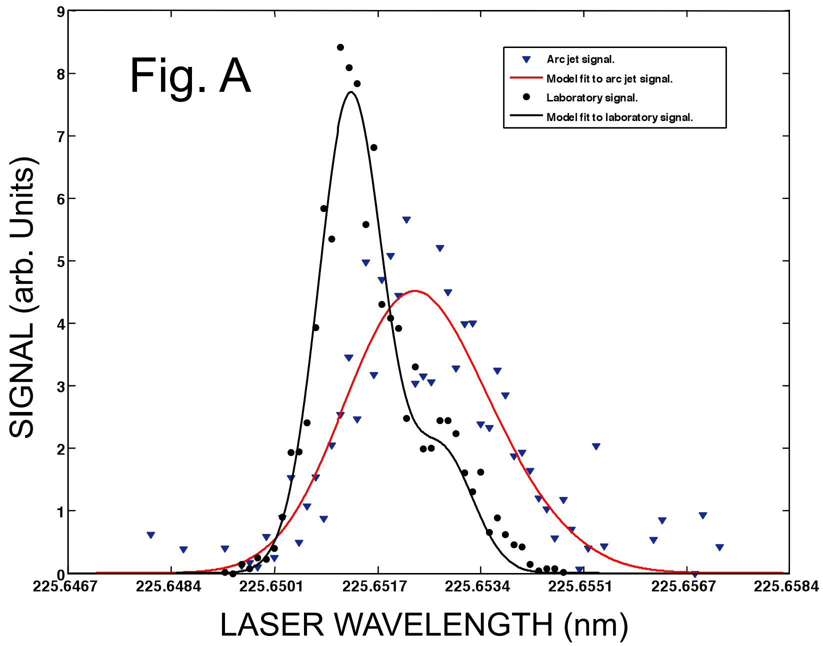


Figure	Facility Data			Atomic Oxygen LIF Results		
	Current (amps)	Power (MW)	Bulk Enthalpy (BTU/lb)	Temperature (deg F)	Velocity (m/s)	Density $x10^{21}$ (m^3)
A	500	1.32	4170	2600	4000	9.5
B	1000	2.33	6670	3420	4400	10.5

Atomic Oxygen LIF Data, (March 2011)

- 185-BTU/ft2-sec and 265-psf stagnation heat rate and pressure
- Measured with a 4 inch diameter flat face

Run 2-3730-1: 90% CO_2:10% N_2



Run 2-3728-1: 65% O_2:35% N_2

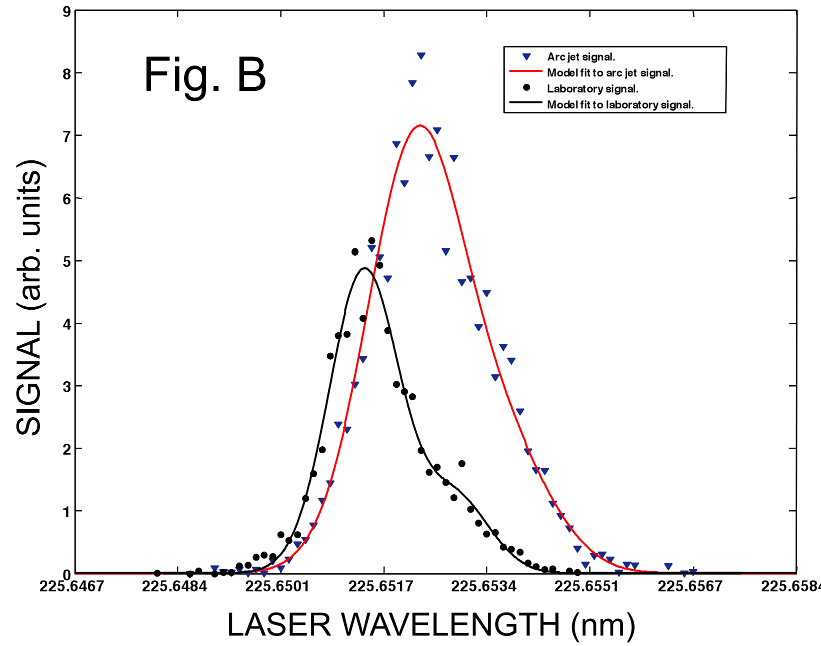


Figure	Facility Data				Atomic Oxygen LIF Data		
	Total Gas Flow (lb/sec)	Current (amps)	Power (MW)	Bulk Enthalpy (BTU/lb)	Temperature (deg F)	Velocity (m/s)	Density x10^{21} (m^3)
A	0.400	750	2.56	4910	3900	2510	2.9
B	0.396	410	1.33	2530	2100	2575	5.7

Conclusions

- The ARMSEF has successfully demonstrated the capability to perform tests <u>safely</u>:
  - with a 90% CO_2:10% N_2 by mass composition and
  - up to 2.56 MW power level
- Existing facility hardware is utilized
  - Electrode erosion rate is comparable to testing with air
- Developed an efficient process to allow rapid transition between the CO_2 and air configurations
- LIF data suggests that full dissociation of the CO molecule is not occurring
  - The atomic oxygen density for the 65% O_2 case is roughly double the density for the 90% CO_2 case
  - The CO within the heater is possibly acting as a shield gas prohibiting rapid oxidation of the electrodes
  - CO dissociation is extremely “hot” and the LIF profile should spectrally broaden to reflect a hotter atomic species with a greater separation of the peaks that indicates an increase in speed.

- Continue to expand the operational envelope with the CO_2 test gas
  - Immediate next goal is to demonstrate the ability to safely test with a 97% CO_2 : 3% N_2 composition
  - Increase power levels and flow rates
    - The design and specifications of a 0.6-lb/sec cryogenic CO_2 delivery system have been determined
    - Expected to be operational in FY12
- Continue to characterize of the flowfield
  - LIF data (centerline and off-axis)
  - Probe sweeps (stagnation heat rate and pressure)
  - Determine the levels of dissociation and generate a map across the operational envelope
- Investigate the differences between CO_2, air, and O_2 rich environments
  - Flowfield characterizations
  - Testing of known materials such as graphite, teflon, PICA, etc.